MULTI-OBJECTIVE WIND FARM CONTROLLER OPTIMIZATION WITH COMBINED THRUST AND YAW CONTROL USING KOOPMAN MODEL PREDICTIVE CONTROL

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Credit: DLR

Motivation Multi-Objective Wind Farm Control

- Wind farms
  - Maximize possible yield per available area, minimize operation and maintenance cost
  - Wake interaction
    - Power losses
    - Additional mechanical loads on downstream turbines

Courtesy: Vattenfall; photographer is Christian Steiness

- Wind farm control objectives
  - Minimize error to reference power / maximize generated power
  - Minimize damage equivalent loads
  - Minimize changes in control input

- Control strategies
  - Axial induction control (AIC), e.g. [Bossanyi et. al 2022], [Pedersen et. al 2020]
  - Wake redirection control (WRC), e.g. [Fleming et al. 2020], [Simley et al. 2022]

Koopman Model Predictive Control for Wind Farms

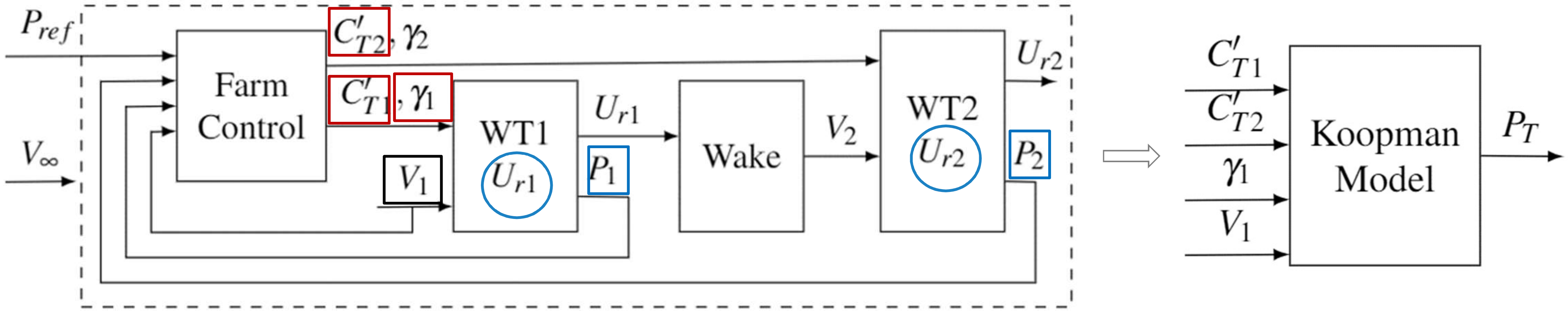
- Koopman model predictive control (MPC) [Cassamo et al. 2021]
  - 100.000 grid points of 3D wind field (SOWFA) → flattened 3D structure to vectors, applied Koopman lifting functions
  - Singular value decomposition for model order reduction and dynamic mode decomposition → MPC

- Realtime, adaptive Koopman AIC MPC [Sharan et al. 2022]
  - Improved power reference tracking with physically motivated Koopman models
  - Real time applicability: Identified Koopman models based on average wind speed at rotor disk
  - Adaptive MPC for wind changes [Dittmer et al. 2022]

- Current work:
  - AIC-WRC: Combination of thrust and yaw control to maximize power yield [Dittmer et al. 2023]
  - How does an additional penalty weight on the yaw angle influence AIC-WRC farm MPC?

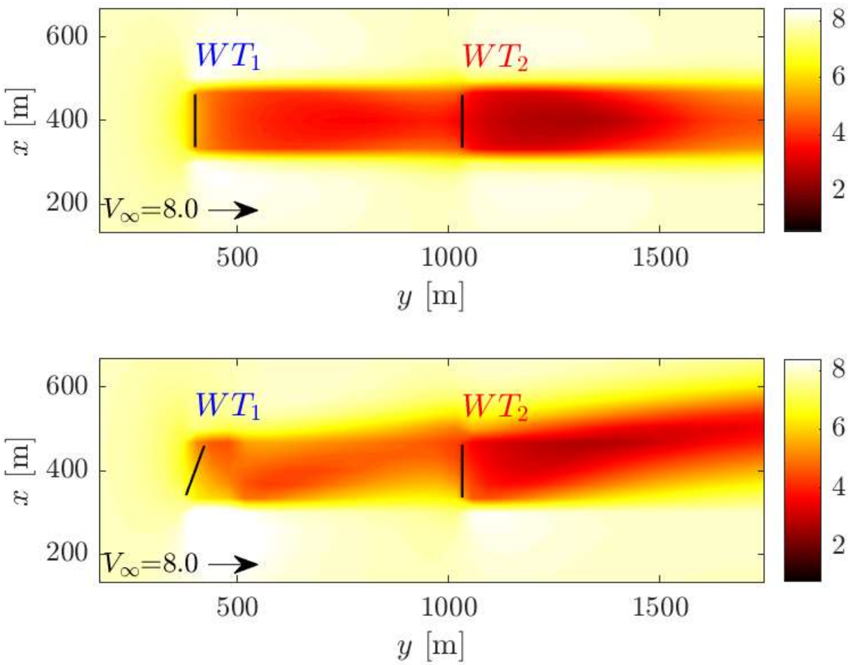
Wind Farm Simulation WFSim

- WFSim [Boersma et al. 2016]: 2D Navier-Stokes equations
- Open-loop data acquisition with constant free-stream wind $V_\infty = 8$ m/s
  - Inputs: Thrust control signals C'_{T1} and C'_{T2}, yaw control γ_1, disturbance wind V_1
  - States: Average wind speeds acting on rotor discs U_{r1} and U_{r2}
  - Output: Total farm power $P_T = P_1 + P_2$
- Closed-loop controller tests: Grid power reference P_{ref}

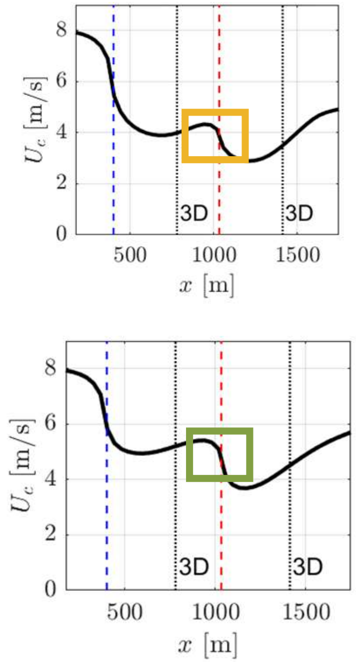


Open Loop Simulation: Wind Fields & Power Yield

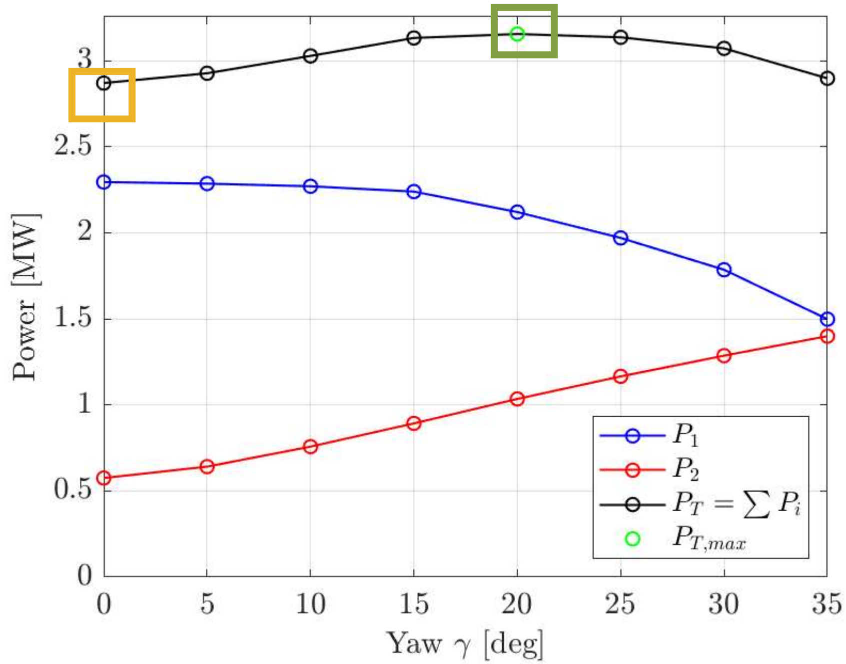
Longitudinal wind



Centerline wind



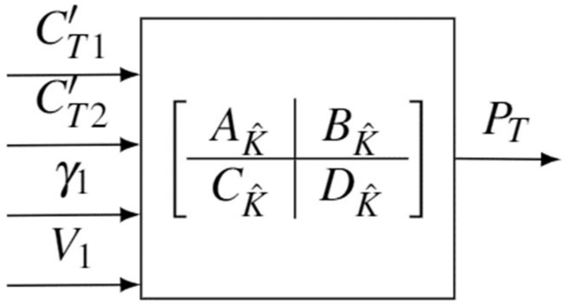
Power vs. Yaw



- Longitudinal wind fields and centerline wind amplitudes at turbines WT1 and WT2
- Decrease of turbine WT1, increase of WT2
- Farm power P_T: Maximum at 20°

System Identification with Koopman

- Use extended input-output dynamic mode decomposition
- Data:
  - $X = [x_1 \quad x_2 \quad \cdots \quad x_{N-1}]: \mathbb{R}^{n_x \times n_{N-1}}$, $X_+ = [x_2 \quad x_3 \quad \cdots \quad x_N]: \mathbb{R}^{n_x \times n_{N-1}}$
  - $U = [u_1 \quad u_2 \quad \cdots \quad u_{N-1}]: \mathbb{R}^{n_u \times n_{N-1}}$
  - $Y = [y_1 \quad y_2 \quad \cdots \quad y_{N-1}]: \mathbb{R}^{n_y \times n_{N-1}}$



- Koopman lifting functions: State x_k and its non-linear combinations $g(x_k)$:

$$\Phi_k^\top = \left[x_k^\top \; g(X_k)^\top\right]: \mathbb{R}^{n_x} \times \mathbb{R}^m \rightarrow \mathbb{R}^{n_\varphi}$$

Lift and append data:

$$L_u^\top = [\Phi(X)^\top \;\; U^\top]$$
$$L_+^\top = [\Phi(X_+)^\top \;\; Y^\top]$$

→

Formulate:

$$\min_{\widehat{K}} ||L_+ - \widehat{K}\, L_u||_F$$

→

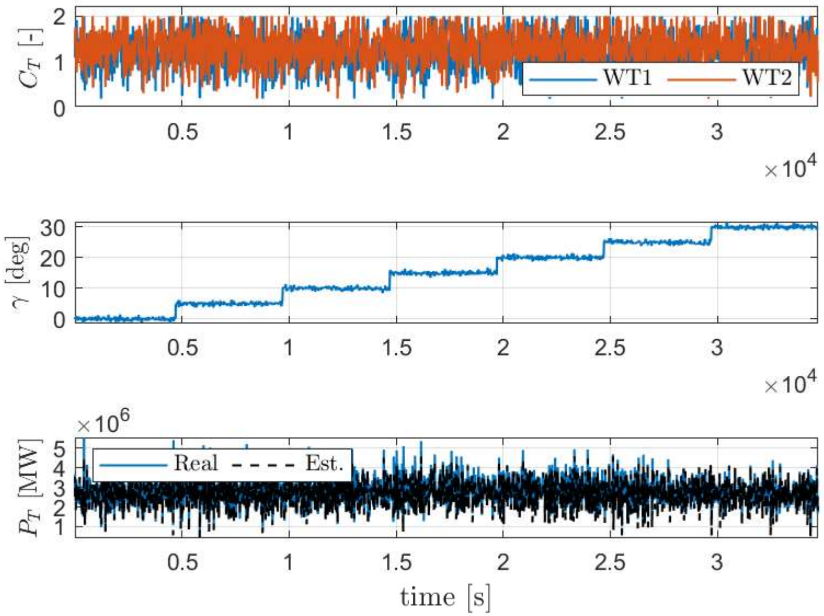
Solve:

$$\widehat{K} = L_+ L_u^\dagger = \begin{bmatrix} A_{\widehat{K}} & B_{\widehat{K}} \\ C_{\widehat{K}} & D_{\widehat{K}} \end{bmatrix}$$

Koopman System Identification Results

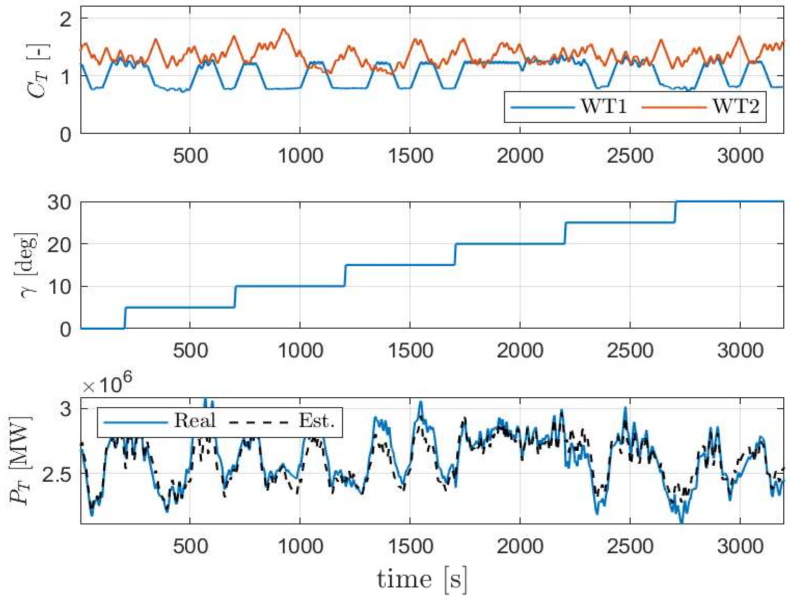
Motivation | Farm Model | Open-Loop Sim. | Koopman | Farm Control | Summary

Identification data (VAF: 94%)



- Thrust control band-limited noise
- Yaw step sweep with added band-limited noise
- 6 states: Effective wind linear, square, and cubic terms

Validation data (VAF 84%)



- Thrust control WFSim test signal
- Yaw step sweep from 0 to 30°
- Variance-Accounted-For (VAF): 84%

Koopman MPC for Wind Farms

- Objectives for wind farm MPC: Minimize **error** and **change in turbine controls**

$$\boxed{\min_{u} J(u)} = \boxed{e^T Q e} + \boxed{\Delta u^T R \Delta u}$$

$$s.t.$$

$$\boxed{\begin{bmatrix} \Phi_{k+1} \\ P_{T,k} \end{bmatrix} = \begin{bmatrix} A_{\hat{K}} & B_{\hat{K}} \\ C_{\hat{K}} & D_{\hat{K}} \end{bmatrix} \begin{bmatrix} \Phi_k \\ u_k \end{bmatrix}}, \quad \boxed{k \in \{1, 2, \ldots, n_h\}}$$

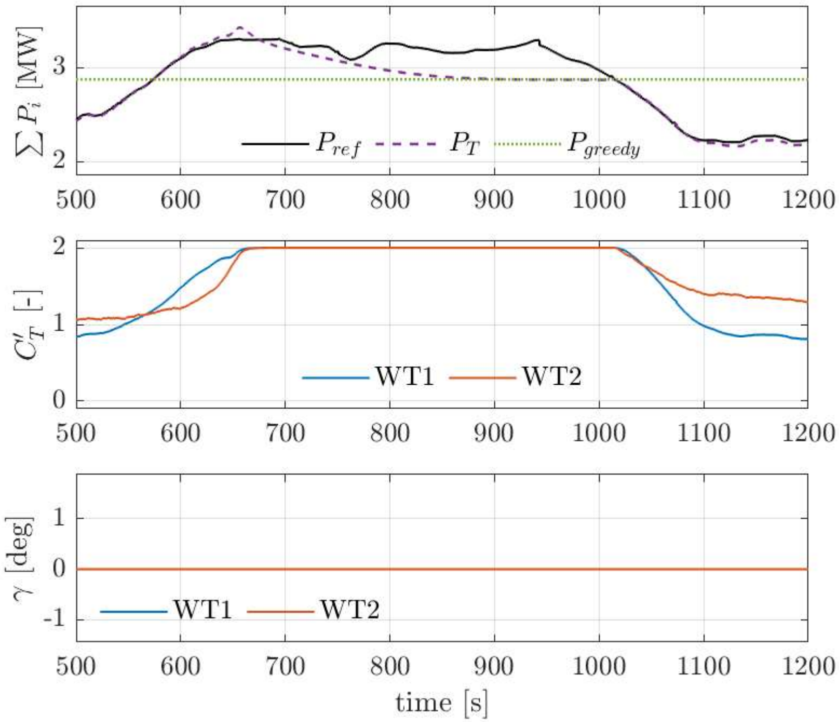
$$e = P_{ref} - P_T = [e_1, e_2, \ldots, e_{n_h}]^T \in \mathbb{R}^{n_h}$$

$$\Delta u = \left[u_1^T - c^T, u_2^T - u_1^T, \ldots, u_{n_h}^T - u_{n_h-1}^T\right]^T \in \mathbb{R}^{n_h n_u}$$

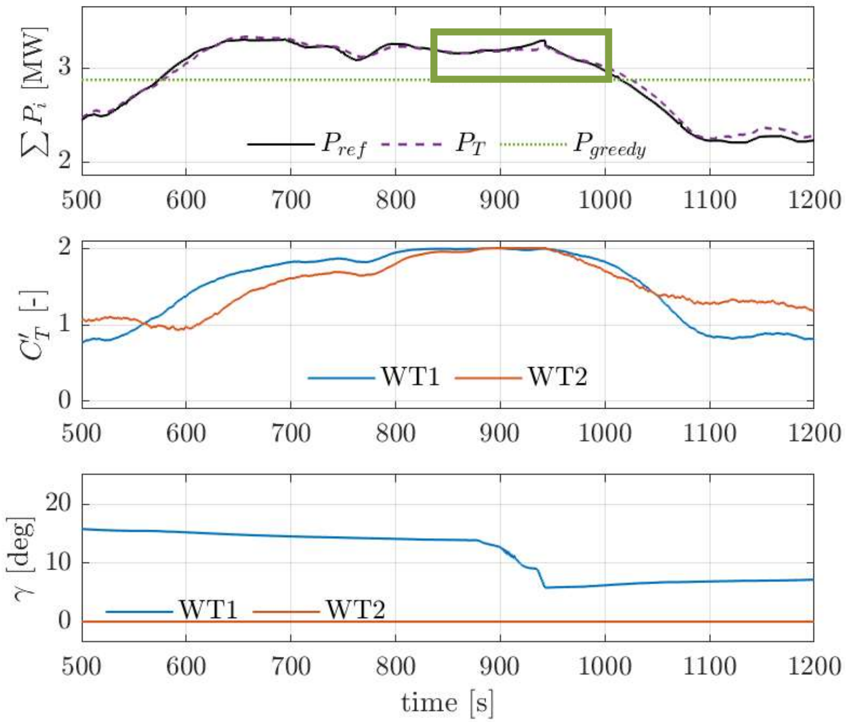
- Use **Koopman wind farm models** to predict wind farm states over a **finite time horizon**
- Solve **optimization problem** to obtain **optimal control inputs** for each turbine under input constraints
- Set the next control inputs and update predictions and optimization problem at each time step

Closed Loop Simulation: AIC vs. AIC-WRC

Thrust control (AIC)



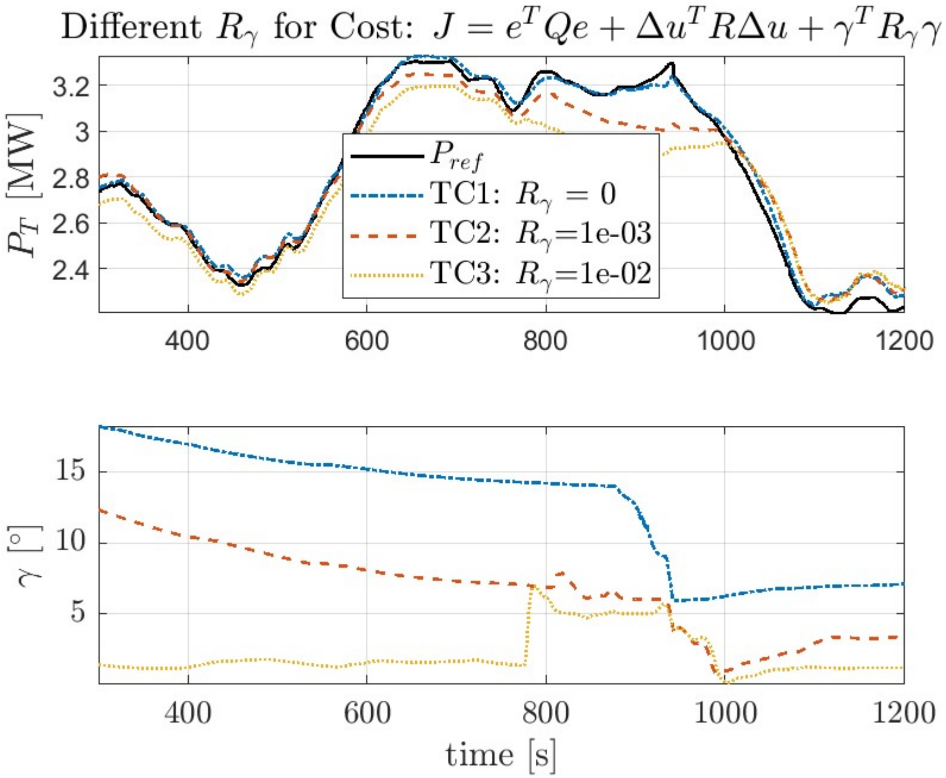
Thrust and yaw control (AIC-WRC)



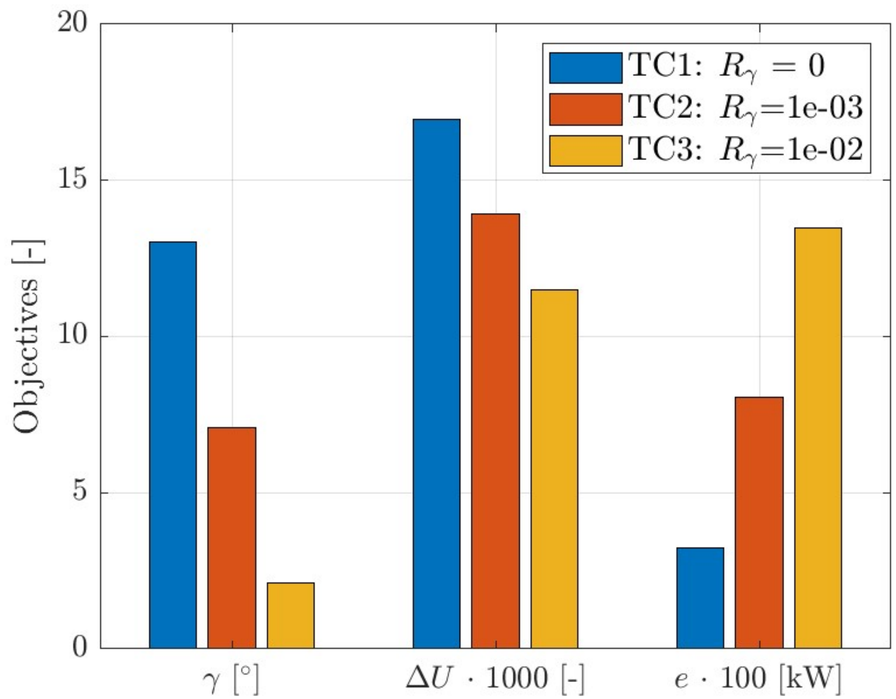
- Reference tracking with thrust control only

- Reference tracking with combination of yaw and thrust control

Different Weights on Yaw Misalignment



- Additional objective: Penalize yaw angles



- Additional yaw angle penalty:
  - Smaller angles and control input changes
  - Considerable larger power error

Summary

Motivation › Farm Model › Open-Loop Sim. › Koopman › Farm Control › **Summary**

- Open-Loop Power increase by WRC (Proof-of-Concept: 10% for two wind turbines in Open Loop Simulation in WFSim)
- Koopman model for MPC: Good variance-accounted-for (> 80%) of system identification
- Good grid reference tracking for Koopman MPC with combined WRC-AIC control

- Outlook
  - Use simulation environment FASTFarm to explicitly use damage equivalent loads
  - Increase the number of turbines and use more realistic wind test cases
  - Use ML/DL techniques (e.g. PINN) for model of MPC

Thank you very much for your attention!